TECHNICAL EXHIBIT FOR

SYSTEM NO. 2

31 May 1955

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INTRODUCTION

System No. 2 comprises the equipment necessary to provide highly reliable communication from air to ground and from ground to air over distances of approximately 2000 miles, and the additional equipment necessary to provide the aircraft pilot with navigation information when the airplane is within 2000 miles of the ground station. It may be taken as axiomatic that both the airborne and ground equipment must operate with great reliability and with the highest degree of navigational accuracy feasible. Additionally, the airborne equipment should be miniaturized to the greatest extent possible to minimize size and weight, and should operate in a manner such as to maintain the highest degree of security possible for the pilot.

Because this contractor has developed certain techniques which permit readily the attainment of the communication range and security required, primary emphasis during the study program just concluded has been placed upon the development of an adequate navigation system. The portions of this exhibit following immediately are concerned, therefore, primarily with a presentation of those factors which have been taken into account during the evolution of the navigation system herein proposed and which serve also to bound the general capabilities of that system.

REVIEW OF EXISTING LONG-RANGE NAVIGATION SYSTEMS

Of the considerable number of long-range navigation systems that have been devised in the past, comparatively few have possessed sufficient merit to result in their installation and operation on even a limited scale. Several of the more important of these systems are identified and described briefly in the paragraphs following immediately, for the purpose of indicating generally the capabilities and limitations of what may be regarded as the best systems known to date.

Perhaps the best known and one of the most widely used long-range navigation systems is Loran. More than 50 Loran ground stations are now installed and in operation in various parts of the world; the great majority of these, however, are located in the United States. Loran is basically a time-difference hyperbolic system utilizing relatively long base lines between the master and slave transmitters employed. The so-called master transmitter emits a coded group of 40-microsecond pulses at repetition rates in the vicinity of 30 groups per second. Following each pulse group emission from the master with finite and fixed delay time, a corresponding pulse group is emitted by either of the two slave stations associated with that master. The difference in time of arrival of the pulse group from the master and that from one of the slave stations serves to define a family of hyperbolic lines of position on and above the earth's surface. Correspondingly, the difference in time of arrival between a pulse group from the master and that from the other slave station serves to define a second family of hyperbolic lines of position. A determination of these two time differences permits a navigator, with the aid of special charts, to fix his position on or above the earth's surface with reasonably high precision.

Loran stations operate at a frequency of approximately 1.9 mc; in consequence, the daytime range is limited to that of the groundwave, which is useful ordinarily over a distance of 300 to 500 miles. The nighttime range is increased by virtue of the fact that propagation via the E Layer permits time difference measurements out to ranges approximating 1400 nautical miles at a maximum. Daytime fixes are normally accurate to within 2.0 miles; nighttime fixes are accurate to within approximately five miles. Transmitter powers employed range from 100 kw to 1000 kw, while the bandwidth required is in the vicinity of 40 kc. The weight of an airborne Loran receiver is about 49 pounds.

An airplane being navigated by Loran enjoys excellent security because it emits no radiation. For the purpose of the program presently under consideration, however, Loran is seriously deficient in both its daytime and nighttime ranges, it requires undesirably high values of transmitter power, and necessitates the use of slave stations separated from the master by distances in the order of 100 to 700 miles.

A second system and one which has been used very extensively in the United States for the purpose of air navigation is known as the LF/MF 4-Course Radio Range. In its normal form, this system is not intended for true long-range navigation, and is utilized generally to distances of not more than 200 miles from the ground station. The 4-course range is basically a time-difference system operating in the 200-400 kc portion of the spectrum. In one form, the ground station employs a total of five vertical antennas, four of these being arrayed to form the corners of a square with 600 ft. diagonals, while the fifth antenna is located at the center of the square. By suitable antenna excitation, the field developed is constant along four lines radiating outward from the antenna system, while the field in other regions appears to consist of time-interlocked A and N signals. When a pilot is flying on course, the A and N signals merge to form a continuous signal; deviation from the normal course results in the production of either A or N signals in the output of the aircraft receiver. Under normal flight conditions, this system permits establishing of a line of position with an over-all uncertainty approximating 3 degrees. The system utilizes groundwave transmission only, and for that reason is very much limited in range. Even though its range could be extended satisfactorily, and its accuracy improved by a very substantial amount, it would be poorly suited to the present application because the on-course signal would define most clearly for the enemy the intended flight path of our aircraft.

A third system of interest is known as Consolan; it is basically the

German Sonne system. This system, too, is a time-difference system which provides the navigator with information concerning his bearing with respect to the Consolan ground station. The system employs a linear array of three vertical antennas, the total antenna base line being three wavelengths long. The system operates at a frequency in the vicinity of 100 kc and normally employs three 10-kw transmitters to excite the three antenna structures. The phase of the r-f excitation of the central antenna of the array is maintained constant, while that of the two end elements of the array is varied progressively with time to result in a uniform rotation in azimuth of the antenna pattern lobes. Power input to the array is keyed in a manner such as to result in the production of "dot" signals in alternate pattern lobes and "dash" signals in the remaining lobes. The lobe structure is such that a pilot can determine his azimuthal bearing with respect to a ground station by counting properly the number of dots or dashes over a specified lobe-pattern interval. It is claimed that this system permits line-of-position determinations with an error in the neighborhood of a 1/3 degree to 1 degree. Special charts are required for use of this system. In many respects, the Consolan system may be regarded as an improved version of the 4-course radio range. This system is regarded as unsuitable for the present application because the antenna array normally extends for a length of more than 5.5 miles and requires a very extensive ground installation.

A further system, and perhaps the best long-range navigation system available at the present time is known as Navarho. The Navarho system operates at a frequency in the neighborhood of 100 kc and employs three vertical radiators, each 625 feet high and top-loaded, arrayed in a triangle measuring 0.36 wavelength on each side. The antenna site requires approximately 800 acres. Each of the antennas is excited by a 15-kw transmitter. The antennas are excited in pairs time-sequentially, which results in the production of a sequence of three figure-eight patterns. A relative measurement of the amplitudes of the three patterns thus produced permits a navigator to determine his bearing with respect to the Navarho ground station. Every fourth pulse emitted from the ground station causes simultaneous excitation of all three antennas to provide a reference signal whose phase difference from that of an ultra-stable oscillator borne by the aircraft permits a determination of range from the ground station.

The Navarho system is claimed to be capable of providing range accuracies in the neighborhood of 1%, and bearing accuracies good to approximately one degree. The airborne receiver occupies about 1 cu. ft. of space and weighs about 50 pounds. Achievement of the range accuracies specified is dependent upon the utilization of an airborne oscillator which provides a frequency stability to within one part in 10^9. Navarho achieves its range by employing both ground-wave transmission and sky-wave reflection from the E Layer. The system would be ideal in many respects for the present application were it not for the fact that it necessitates the use of very high cost and bulky ground transmitter and antenna installations, and produces continuous signal radiation over both friendly and enemy territory.

GENERAL CONSIDERATIONS PERTAINING TO RADIO NAVIGATION SYSTEMS

Basically, all radio navigation systems operate by serving to establish identifiable lines of position on the earth's surface and in the space above. The intersection of any two such lines of position permits the establishment of a fix. The various systems that may be utilized differ primarily in the methods employed for establishing lines of position and in the techniques employed in using information derived from such lines. The establishment of a fix may be accomplished if the navigator knows (a) his range from two ground stations whose precise location is known to him, (b) his bearing from two ground stations whose precise location is known to him, or (c) his range and bearing from one ground station whose precise location is known to him. Redundancy in the information available to the navigator will generally be of assistance to him in minimizing the error of his determinations.

Radio range determinations are most readily accomplished by measuring the time required for a pulse signal to traverse the round trip from aircraft to ground and return, or vice versa. This time value multiplied by one-half the velocity of light gives the radio-signal path length between aircraft and ground station. Determination of the bearing of a radio signal source with respect to a receiving system may be accomplished by measurement of the radio-frequency phase difference between the signals received on two or more antennas whose separation and orientation are known accurately, or by measuring the difference in signal pulse-envelop times of arrival at two or more such antennas. The latter method generally requires much greater separation of the receiving antennas for a given degree of precision in bearing determination, or the utilization of pulses of much shorter duration than are required for r-f phase comparison.

Radio determinations of both range and bearing are influenced markedly by the characteristics of the medium of signal propagation, and in a practical sense the limits on accuracy of navigation attainable are determined almost completely by propagation medium characteristics.

FACTORS INFLUENCING SIGNAL PROPAGATION OVER LONG DISTANCES

When low-frequency radiation is employed, ground-wave transmission may be useful over distances as great as 500 miles to 1000 miles from the transmitter; at greater distances, the signal reflected by the ionosphere, termed the sky wave, is of much greater utility than the ground wave. As the transmitting frequency is increased, the range over which the ground wave is effective decreases, and sky-wave transmission becomes increasingly more important.

Because it will be of assistance in assessing the value of the techniques proposed in this exhibit for overcoming some of the limitations upon attainable navigation system accuracy imposed by the characteristics of high-frequency ionospheric propagation, the following brief discussion of some of the pertinent characteristics of ionospheric propagation is presented.

The ionosphere is that portion of the upper atmosphere, extending from a height of about 60 km to upwards of 500 km, in which the degree of ionization of the gases present provides free electrons in numbers sufficient to exert an effect upon electromagnetic wave propagation. Fig. 1 indicates schematically the principal features of ionosphere structure. During the daytime, three normally well-defined strata capable of reflecting radio waves exist. They are known, in the order of increasing height and electron density, as the E, F_1, and F_2 layers, and are centered at heights of about 110 km, 225 km, and 300 km, respectively. Below the E layer is a region of low electron density called the D layer which strongly absorbs waves of certain frequencies and reflects waves of very low frequency.

The electronic density of all of the layers decreases at nighttime, this effect being particularly pronounced in the case of the E layer. Also, at night the F_1 and F_2 layers merge into a single F layer. It will be noted from Fig. 1 that during periods corresponding generally to the hours of sunrise and sunset a significant change in height of the F_1 and F_2 layers occurs, in consequence of which these layers exhibit a "tilt" with respect to the earth's surface immediately below. While tilt occurs with considerable regularity during the sunrise and sunset periods, it can occur at other times of the day or night.

The ionosphere exhibits pronounced diurnal and seasonal variations, upon which are superimposed long-period variations corresponding with the 11-year sunspot cycle. The E layer maintains a nearly constant virtual height of about 110 km throughout the day and from season to season. The F_1 layer, which exists only during the daytime, exhibits a mean virtual height in the neighborhood of 225 km, but may fluctuate in height to the extent of 30 km or more during the day. The F_2 layer exhibits pronounced diurnal variations in height about its mean value of approximately 300 km.

The propagation of a sky-wave signal between two points on or above the earth's surface takes place by combinations of reflections from layers of the ionosphere and the earth's surface. Each combination of reflections is termed a mode of propagation. A few typical modes are indicated in Fig. 2. Referring to this figure, a signal leaving the transmitter T may arrive at the receiver R after reflection in the E layer at point A. This mode would be identified as a 1-hop E mode, because it involves a single reflection from the E layer. The signal might also be propagated between these points by virtue of reflection at point B from the F_1 layer or by reflection at point C from the F_2 layer. It is possible, too, for signals to be propagated from T to R after two or more ionospheric reflections. Thus, a signal leaving T may experience a first reflection at point D which directs the signal back to the earth's surface at point E; the earth then reflects the signal back to the ionosphere where a second ionospheric reflection at point F redirects the signal to the receiver R. This process would be identified as a 2-hop E mode. The situation existing for a 2-hop F mode is indicated with layer reflection taking place at points G and H.

It will be evident from Fig. 2 that the length of path followed by a radio wave propagated from T to R may be substantially greater than the distance d measured between these points along the earth's surface. The actual difference between radio path length and the surface separation between T and R is a function of the distance d, the height of the reflecting layer, and the number of reflections involved. The actual distance separating T and R may be determined with considerable precision if the radio path length and the elevation angle of the path are known. Fig. 3 indicates the manner in which the distance d may be determined for the flat earth case when the path length L and the vertical angle of arrival δ are known. An equivalent technique may be employed for the spherical earth case.

It will be evident from the discussion in the paragraphs immediately preceding that a reasonably accurate determination of range could be made if the path length L and the associated vertical angle of arrival δ were known for any one of the active modes of propagation. It will be equally apparent that mode separation must be achieved to permit accurate ranging. This contractor has gained experience in effecting mode separation by the transmission and reception of signal pulses of such short duration that overlapping in time of the pulses received over two or more active paths is avoided. It is proposed to utilize this technique in the high-frequency navigation system with which this exhibit is concerned.

Accurate determination of the bearing of a radio source with respect to a receiving center by means of comparison of the radio-frequency phase difference between the signals received on two or more antennas necessitates also that mode separation be effected. For this reason, again, the utilization of short duration pulse transmission would tend to reduce materially the errors in bearing determination on high-frequency signals.

The ionosphere frequently exhibits abnormalities which exert a pronounced influence upon wave propagation. It is often noted that waves are reflected from the E region at frequencies greater than those which the E layer is normally capable of reflecting. This phenomenon is attributed to the existence of clouds of unusually high electron density within or slightly above the E layer, which form the so-called sporadic-E layer. At times the electron density in these clouds is greater than that present in the F_2 layer.

Another abnormality of the ionosphere is termed the "Dellinger effect" or blackout; this phenomenon relates to the abrupt disappearance of sky-wave signals for periods ranging from less than a minute to several hours, and is caused by the sudden formation of high ion-density regions between the earth and the normal ionosphere. This effect is noted simultaneously over the sunlit portion of the earth's surface and is attributed to bursts of intense ionizing radiations originating in solar eruptions. Another abnormality occurring with some frequency, and attributed to bombardment of the upper atmosphere by charged corpuscular radiation from the sun, is known as an "ionospheric storm". Such storms generally last for several days, during which high-frequency signal absorption is unusually great and layer structure tends to be poorly defined.

It will be apparent that the percentage of time during which a high-frequency navigation system can be employed is limited by the frequency of occurrence and the duration of blackouts and severe ionospheric disturbances and storms. In general, the percentage of outage time of the navigation system arising from such causes might be expected to exceed the outage time on long-distance communication circuits by a relatively small amount.

It has been noted by investigators in the field of radio propagation that the azimuthal angle of arrival of radio waves does not always coincide with the value that would be obtained if the signal were propagated along the great circle path joining transmitter and receiver. C. B. Feldman, for example, reported in 1939 on a series of observations made on signals received in Holmdel, New Jersey from Rugby, England, in which he noted occasional deviations as large as 30 degrees to 40 degrees from the great circle path. His report indicated that such deviations occur rarely, if ever, during the daytime, but may be observed at night during the early and terminating phases of ionospheric storms. Under other conditions, the azimuthal direction of arrival coincided within one or two degrees with that of the great circle propagation path.

Although large azimuthal deviations are observed on occasion, it is comparatively unusual to find complete drop-out of the signal propagated along the great-circle path joining transmitter and receiver. Upon noting that the time required for signal propagation along the deviated path must always exceed that for the signal traversing the great-circle path, it will be evident that propagation mode separation achieved through the utilization of transmitted pulses of short duration can be employed to discriminate heavily against signals arriving over deviated paths.

Determinations of radio-source bearing angle and vertical angle of signal arrival at a given receiving site are made most directly by r-f phase comparison of the outputs of two or more receiving antennas. If these measurements are to be made with precision it is necessary that the received-signal field exhibit a high order of phase stability in each of the active propagation modes. Little data appears to exist with respect to such stability, and it is the uncertainty with respect to this characteristic of propagation that renders the realizeable performance of the system proposed open to a certain amount of question. Obviously, this question must be resolved experimentally at a very early date.

The only apparent alternative to the use of short-pulse transmissions to effect mode separation for the purpose of increasing the accuracy in both range and bearing determination is that of employing multi-unit steerable antennas (MUSA). MUSA systems have been employed for this purpose, but the degree of steering that can be attained readily is rather severely limited and the over-all size of the antenna structures required is inconveniently large.

Because the maximum frequency of the signal that can be reflected by each layer of the ionosphere is dependent upon the electron density in the layer and the angle of incidence of the signal upon the layer, it is possible in many cases to select the operating frequency employed in a manner such as to insure that only one propagation mode will be active. Unfortunately, the range of distances and the percentage of time for which such frequency selection can be employed to suppress unwanted modes is not compatible with the requirements on system performance with which we are concerned.

Regardless of the techniques employed for range and bearing determination, the received signal amplitude must exceed some minimum value referred to the root-mean-square value of the noise superimposed upon the signal if an acceptable order of accuracy in determination is to be achieved. The minimum acceptable signal-to-noise ratio will generally be a function of the type of ranging and bearing determination techniques employed.

If the virtual reflecting surface of an ionospheric layer is parallel to the earth's surface immediately beneath the point of reflection, the angle of signal reflection is equal to the angle of incidence of the signal on the ionosphere and the reflected wave ray lies in the plane of incidence. If, however, the ionosphere exhibits a tilt, the path of the reflected ray is distorted in a manner such as to cause error in both range and bearing determination regardless of the method of determination employed. The E layer rarely exhibits sufficient tilt to cause significant error in range or bearing determinations; F layer tilt, however, may be much more pronounced at times and can cause undesirably large error. No readily applicable technique to minimize greatly or to eliminate errors arising from F layer tilt is known.

In summary, ionospheric signal propagation influences the performance of radio navigation systems because:

a. The length of the path traversed by a radio signal between a transmitter and a receiver is always greater than the distance along the earth's surface between those points.

b. The signals received at two antennas separated by a number of wavelengths may not exhibit phase stability.

c. The signal may traverse two or more paths between transmitter and receiver.

d. The principal component of the received signal may have traversed a path deviating appreciably from the great-circle path joining transmitter and receiver.

e. The signal may have experienced distortion in range or bearing because of ionosphere layer tilt.

f. The signal may have been distorted severely by the superposition of noise originating in the medium of propagation.

The uncertainties created in range and bearing determination by all of the factors except the last one identified tend to decrease as the transmitting frequency employed is decreased, and it is for this reason that the best of the previously developed long-range navigation systems operate in the Low-Frequency band. Low-frequency operation entails, however, the use of comparatively high values of ground transmitter power, exceedingly large and expensive antenna structures, and comparatively large and unobstructed land areas for the installation of adequate antenna and ground facilities. Such installations tend to be very costly and do not lend themselves well to temporary installation for short-term usage. For these reasons, it has been considered essential to investigate the feasibility of performing the navigation function by utilizing high-frequency transmission.

A considerable number of approaches to the solution of the navigation problem have been investigated in great detail. In general, the objective has been that of providing a system capable of yielding range information accurate to within approximately 1%, or bearing information accurate to 1/2 degree, or both of these quantities with corresponding error limits. An additional objective has been that of devising a system which would utilize to the greatest extent possible existing antenna and transmitter facilities to minimize the amount of engineering, and therefore, the time period required to implement the system. This contractor is well aware of the long periods of time and the tremendous amount of engineering effort that have been involved in the development of existing navigation systems, and has predicated his approach to the solution of the navigation problem, to the greatest extent practicable, upon the utilization of techniques with which he has gained previous experience. Not all of the uncertainties that exist with respect to performance of the system herein proposed can be resolved by analytical or brief experimental programs. Accordingly, the program proposed entails a certain measure of risk, for none of the critical techniques to be employed has been evaluated previously for comparable functions. Measures to provide back-up protection to the program have been studied, however, and are discussed more fully under the section of this exhibit entitled "Program Proposed".

25X1X3 PRINCIPLES OF OPERATION OF THE PROPOSED SYSTEM

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PROPOSED ENGINEERING PROGRAM

Of foremost importance to the conduct of the communication and navigation program is an early determination of the validity of certain concepts upon which performance of the proposed system is based. In particular, it is a requirement for successful operation of the system that the radio-frequency signals received from the aircraft via each active mode of

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propagation show a high order of phase stability at points on the earth's surface separated one from the other by distances on the order of a half-dozen wavelengths. Such experimental evidence related to this matter and with which we are familiar suggests that the required phase stability does exist for at least part of the time, but the evidence is scanty and in such form as to require considerable extrapolation before its direct application to the navigation problem.

Failure on the part of nature to provide phase stability of the degree required would not automatically rule out the navigation system herein proposed, but it would reduce its utility by a substantial factor. Such failure also would raise serious question as to the justification for proceeding with development of the navigation system proposed in preference to using an alternative system, even though the latter were functionally less attractive. It should be borne in mind, at this point, that no doubt exists with respect to successful performance of the communication system proposed.

By way of compressing a maximum of accomplishment into a minimum of time, this contractor proposes, unless directed otherwise, to pursue the following engineering program:

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APPENDIX A

The following analysis explains the method used in determining the accuracy of measurement required to secure adequate navigation data.

Symbols used in this analysis are defined below:

θ	=	azimuth angle in radians
δ	=	elevation angle in radians
L	=	apparent radio range
R_o	=	radius of the earth
d	=	true range from base station to aircraft
$\Delta\beta$	=	lateral error of position
ϕ	=	electrical phase angle
m	=	number of wavelengths separating adjacent range and bearing antennas
$\varepsilon_{\alpha\beta}$	=	the angle between the normal to the wave front and the line joining antennas α and β

The most elementary case to be considered is that of a plane earth and a plane ionosphere parallel to the earth. True range of the aircraft can be computed from the measured apparent-radio-range and the measured elevation angle by means of the relation

$$d = L \cos \delta \, . \tag{1}$$

Errors that appear in the true range when the apparent radio range and the elevation angle are not measured accurately can be obtained by taking the total differential of equation (1)

$$\Delta d = (\Delta L) \cos \delta - (\Delta\delta) L \sin \delta \; .$$

At a range of 2000 miles and an assumed F-layer height of 180 miles, this equation becomes,

$$\Delta d = 0.98 \, (\Delta L) - 360 \, (\Delta\delta) \; . \tag{2}$$

Thus, a 10.2-mile error in the measured value of the apparent radio range or a 1.5-degree (1/36 radian) error in the measured value of the elevation angle will result in a 10-mile error in the calculated true-range. Again, assuming an F-layer height of 180 miles but a true range of 250 miles, an error of 17.5 miles in measurement of radio range, or an error of 1.5 degrees in measurement of vertical angle of arrival will result in an actual range error of 10.0 miles.

The error equation for the lateral direction is given by,

$$\Delta\beta = d\,\Delta\theta \quad ,$$

which for a 2000-mile range becomes ,

$$\Delta\beta = 2000\,\Delta\theta \quad .$$

At this range, therefore, a 0.3-degree (1/200 radian) error in measurement of azimuth angle corresponds to a 10-mile lateral error of position. At close ranges, the lateral error due to error in the measurement of azimuth angle can be neglected.

When the spherical earth and spherical ionosphere case is analyzed, somewhat more complex equations result than those applicable to the plane earth case. Of primary interest is the spherical-earth error equation which, for an assumed true range of 2000 miles and a reflecting-layer height of 180 miles, becomes

$$\Delta d = 0.94\,(\Delta L) - 484\,(\Delta\delta) \quad . \tag{3}$$

A comparison of equation (3) with equation (2) shows that there is little change in the required accuracy of the radio-range measurement, but a need to improve the accuracy of elevation angle measurement to about 1.1 degrees.

At a range of 250 miles, the spherical earth analysis reduces to that of the plane earth. Similarly, there is little difference between lateral errors indicated in the spherical earth analysis and that of the plane earth.

Actual values of elevation and azimuth angle are determined by making electrical phase difference measurements on the wave front arriving at three separated receiving stations. The phase difference between the wave fronts at two of these stations is given by

$$\phi_{\alpha\beta} = 2\pi m \cos \mathcal{E}_{\alpha\beta} \quad .$$

The error equation corresponding to the above is

$$\Delta\phi_{\alpha\beta} = 2\pi m \sin \mathcal{E}_{\alpha\beta}\, \Delta\mathcal{E}_{\alpha\beta} \quad .$$

When the three ground stations are located at the corners of an equilateral triangle, it can be shown that $\Delta\mathcal{E}_{\alpha\beta}$ can be made to correspond to $\Delta\theta$ or $\Delta\delta$ to within a multiplicative factor lying between 1, and the value of cos 30°. Furthermore, if the correct pair of ground stations is selected, the minimum value $\mathcal{E}$ can assume at maximum range is 3.5 degrees for the elevation case, and 60 degrees for the azimuth case. In consideration of the above, and when m = 3, the error equations become,

$$\Delta\phi_{azimuth} = 14.2 \Delta\theta \quad ,$$

$$\Delta\phi_{elevation} = 1.0 \Delta\delta \quad .$$

Thus, for an accuracy of 0.3 degree in azimuth angle, the phase angle must be measured to within 4.26 degrees; while for an accuracy of 1.1 degrees in elevation angle, the phase angle must be measured to within 1.1 degrees. These accuracies are necessary to produce an over-all accuracy of 10 miles in both range and lateral directions at a 2000-mile range.